logical relationship between variables, a reduced-order physics-based model, or even a statistical or machine learning model.

[0011] A battery system with integrated thermal management as described can be utilized to perform anomaly detection, diagnostics, or prognostics of battery packs. Anomaly detection uses algorithms to simply identify whether the pack is undergoing typical or anomalous operating conditions. If an anomaly is detected, the BMS should provide guidance/recommendations based on the severity of the anomaly. Diagnostics takes anomaly detection a step further and pinpoints the location and cause of the anomaly. Diagnostics can aid in identifying the root cause of a failure or can aid in maintenance. Prognostics aids in predicting the onset of failure and can provide advanced warning before a pre-determined failure threshold. All of the above can be used to improve safety or performance, reduce costs, and prolong the useful life of a battery.

[0012] In conjunction with predicting temperature distribution by models, thermal sensors can be used to detect local temperatures within the battery cell/pack Error! Reference source not found.; however, they can add to the cost, weight, and complexity of the battery pack and are susceptible to failure themselves. In large battery packs, sub-optimal placement of temperature sensors could delay the detection of a thermal event. Therefore, it is necessary to optimize the location and the number of temperature sensors to maximize the safety of the pack. Several prior works have identified the need for thermal sensors within a battery pack.

[0013] U.S. Pat. No. 8,487,588 B2 describes a battery pack consisting of cells, thermal sensors, and controllers to convert the thermal measurement to an electrical signal. U.S. Pat. No. 8,620,506 B2 discloses a controller to regulate the temperature of a battery within an operating temperature. However, the optimization of the number of sensors and anomaly detection methods are not discussed.

[0014] The presence of thermal sensors alone does not provide adequate safety for a battery pack. U.S. Patent 2011/0090666 A1 reports mounting arrangements for thermal sensors in a battery pack. The claim focuses on sensor placement for streamlining the manufacturing process, but does not relate to sensor placement for control or battery management purposes. U.S. Pat. No. 8,084,154 B2 discloses a battery pack thermal management apparatus and methodology. The prior work determines whether the battery needs to be heated based on temperature measurements and comparing the measurements to the current operating conditions. Safety and the risk of thermal runaway are not considered. U.S. Patent 20140067297 describes a method for optimally managing the temperature of an electrochemical storage system based on an online or offline model to prevent risks of thermal runaway. However, this method does not discuss an approach to optimal sensor placement or the number of sensors optimally needed to estimate temperature distributions.

SUMMARY OF THE INVENTION

[0015] The present invention is a battery pack with integrated thermal management that is built upon laboratory experiments or a full simulated design of experiments (DOE) for developing thermal profiles in batteries under a wide-range of operating conditions. The thermal profiles are embedded in the battery management system in the form of look-up tables or equations and compared to sensor measurements to determine deviations from healthy behavior.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The present invention is described with respect to particular exemplary embodiments thereof and reference is accordingly made to the drawings in which:

[0017] FIG. **1** is a schematic illustrating a battery pack with temperature sensors.

[0018] FIG. **2** is a schematic of a battery pack with sensors at discrete locations reflected in a coordinate system for a look-up table or equation.

[0019] FIG. **3** is a flow chart for implementation of thermal modeling and sensing for battery anomaly detection and health assessment.

[0020] FIG. **4** is a schematic of both a battery pack with batteries connected in series (FIG. **4**A), and in parallel (FIG. **4**B).

[0021] FIG. **5** is a plot of temperature measurements for three test samples at different discharge rates.

[0022] FIG. **6** is a plot comparing temperatures from a computer-aided modeled result vs measured battery cell temperature.

DETAILED DESCRIPTION OF THE INVENTION

[0023] Temperature monitoring and modeling are not limited to anomaly detection and safety. This same strategy can be used for many purposes including, but not limited to, the design of control strategies, implementation of active thermal management, assessment of the remaining useful life of the battery, or determination of warranty coverage.

[0024] A general example of the embodiments of the invention is described below with reference to the accompanying drawings. The invention is not limited to the construction set forth and may take on many forms embodied as both hardware and/or software. The invention may be embodied as an apparatus, a system, a method, or a computer program. The numbers are used to refer to elements in the drawings.

[0025] A battery pack is composed of at least one or more cells connected in various series and parallel combinations, such as shown in FIGS. **4**A and **4**B. In some embodiments individual cells are in the form of flat plate-like structures, which can be stacked to form the battery pack. In other embodiments the batteries can be cylindrical and stacked side by side. In some embodiments the battery packs pay be passively cooled, such as by air. In other embodiments they can be actively cooled such as by passing air over the pack or enclosing the pack through which enclosure cooling fluids are passed.

[0026] The cells can have different locations within the battery pack. It is to be noted that placement of cells within a battery pack can influence temperature fluctuations at different locations within the battery pack. If there is an obstruction in the cooling line between groups of cells, the inefficient cooling could be detected through the abnormal temperature distribution. With reference to FIG. (**1**), in one embodiment, there will be at least one temperature sensor for each cell in the battery pack. However, the invention is not limited to this case, and depending on the costs or ease